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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

FRETTING
CORROSION

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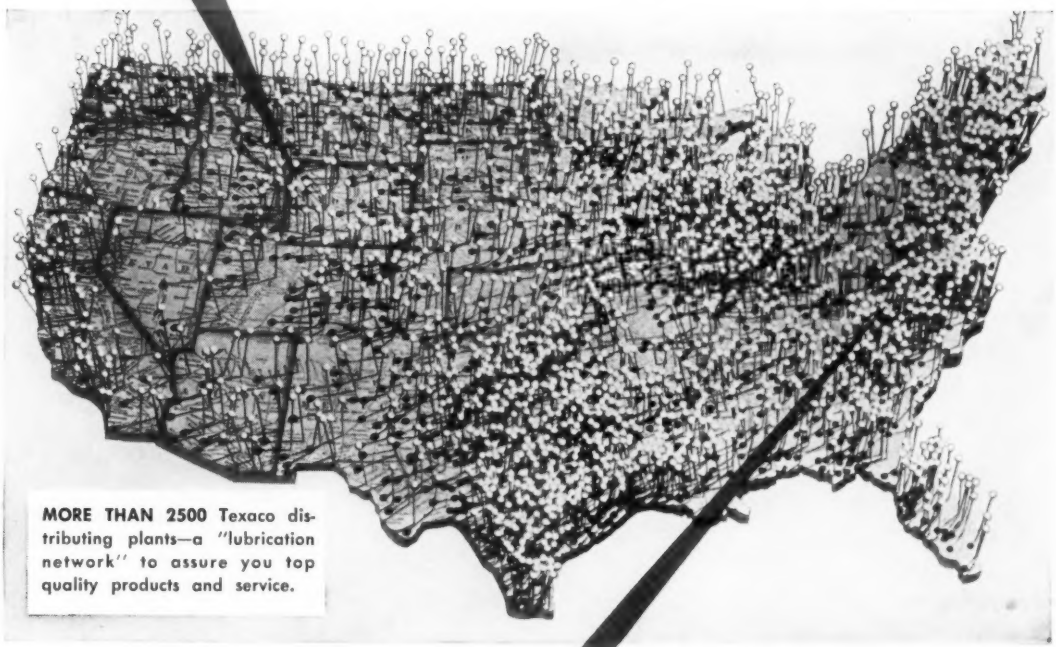

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LUBRICATION

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FRETTING CORROSION

"FRETTING CORROSION" is one of the names given to a particular type of corrosion found on the contact areas of loaded metal surfaces subject to oscillatory or vibrating motion. The phenomenon is also known as "false brinelling" and as "friction oxidation." The latter term is descriptive of the mechanism by which the oxidation or corrosion is believed to occur, and is widely used in the anti-friction bearing industry. As correctly used, however, all three expressions apply to the same problem, which is more prevalent in machine parts than might generally be supposed.

Fretting corrosion, as we have chosen to call it, is probably one of the oldest mechanical-chemical problems. Only in the last two decades, though, have specific cases of fretting corrosion been differentiated from electrolytic and chemical corrosion or from brinelling (pressure indentation) of loaded surfaces.

In fact, it is often difficult to distinguish entirely between the damage caused by fretting corrosion and that caused by brinelling due to excessive loads or impact. The occurrence of a reddish or brown iron oxide residue is often the only clue upon which a diagnosis of fretting corrosion may be given as the true source of difficulty in a given instance.

ONE technical problem associated with lubricants and lubrication that is still only partially solved is that of fretting corrosion, also known as false brinelling or friction oxidation. By any of these names, this is a particular type of metal corrosion or oxidation which occurs on the contact areas of loaded metal surfaces subject to oscillatory or vibrating motion

Like many other such problems, fretting corrosion has yielded somewhat to the impact of scientific investigation and study by industry and industrial laboratories. Even though all of the many questions involved can not be answered at this time, it is not too optimistic to expect that continued investigation will result in a more complete understanding of the problem. This understanding then will permit the development of more effective, reliable methods of solving fretting corrosion problems.

Another complication in recognizing fretting corrosion as the primary agent in a bearing or machine part failure is that secondary effects, such as galling or even welding of metal surfaces, may occur as a result of the initial surface disruption, and may reach such proportions as to obscure all evidence of the fretting corrosion which started the trouble. Fatigue failures, developing as a result of surface imperfections caused by fretting corrosion, sometimes result in cracking or fracture of the parts involved, with resultant damage that obscures the signs of the fretting corrosion to all but the most experienced investigators.

REVIEW

One of the most commonly cited and most wide-spread occurrences of fretting corrosion developed in wheel bearings of automobiles shipped by rail and highway transport from the Detroit area a little over ten years ago. For the relatively short period during which difficulty was experienced, this problem resulted in one of the greatest monetary losses known to be due to fretting corrosion, inasmuch as replacement of at least the front wheel bearings on many thousands, if not hundreds of thousands, of cars was involved.

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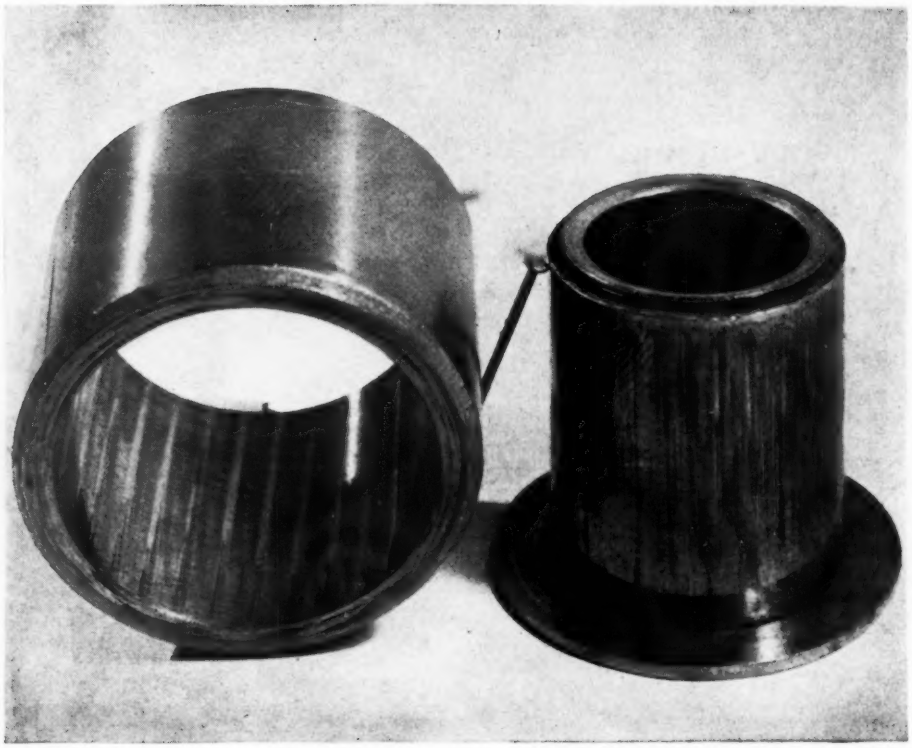

Courtesy Air Materiel Command U. S. Air Forces

Figure 1—False brinelling (fretting corrosion) of needle bearing.

The fretting corrosion, which was given the name "false brinelling" because of its resemblance to pressure indentation of the bearing races, was found to be a result of vibratory contact between the balls or rollers of the bearings and the races, caused by motion of the rail cars or trailers. Trouble was experienced both with the automobiles resting on their wheels, restrained by cables and blocks under the tires, and with automobiles supported on blocks under the axles, with the wheels unsupported. In the first instance, the slight motion or vibration of the automobile induced by motion of the freight car and by inertia of the auto's mass was sufficient to produce damage in the wheel bearings, even though the wheels themselves were unable to turn. In the case of the autos supported on the axles, oscillation of the front wheels through even extremely small angles, induced by vibration and by inertia of the wheels, coupled with the bearing loads due only to the weight of the wheels, was also sufficient to result in false brinelling or fretting corrosion at the contact areas on bearing races.

Similar damage has been reported to anti-friction bearings of electric motors and many other types of machinery when shipped assembled in freight cars. Ordinary means of restraining the rotors or shafts of such equipment are not always effective due to the extremely small motion which may be sufficient to produce the corrosion.

Fretting corrosion also occurs frequently on the races and balls or rollers of anti-friction bearings which are under so-called static loads but are subjected to oscillation or vibration. This includes many aircraft control bearings, which may turn through only a very few degrees or may be subjected to continuous vibration from power plants or aerodynamic forces while operating. Even the most advanced machines are not immune, since fretting corrosion has been experienced in the rotor hub bearings of certain helicopters. The bearings involved, which allow for cyclic change of pitch of the rotor blades as the rotor revolves, normally oscillate through only a few degrees and are also necessarily subject to vibration.

Vibration is also a cause of fretting corrosion in many so-called "fixed" contact surfaces, such as railroad rail end joints. Aircraft engine and variable-pitch propeller parts, either clamped and subject to vibration or else operating with limited motion, have been susceptible to severe fretting corrosion in some instances.

Reports have been made of fretting corrosion in many other different operations and types of equipment. These fall into the general classification given

Figure 2—Galled arbor from bearing test machine. Cantilever loading of test bearing on section just to left of shoulder, as viewed above, results in flexing of galled tapered portion of arbor in tapered housing, with result as shown.

in the first sentence of this article; namely, they involve oxidation of the contact areas of loaded metal surfaces subject to oscillatory or vibrating motion.

NATURE OF THE FRETTING CORROSION PROCESS

The nature of the process by which fretting corrosion takes place in ball and roller bearings and other rolling, sliding, or clamped machine elements has been studied by a number of investigators. Many of these have published their findings, which in most cases are limited by the special nature of the problem under study. Nevertheless, a significant amount of fundamental information has been developed. This information provides an acceptable explanation of the mechanism by which fretting corrosion occurs, as well as general conclusions regarding the effect of such variables as load, speed, materials, and lubricants upon the severity of corrosion.

Of the experimental investigations that have been

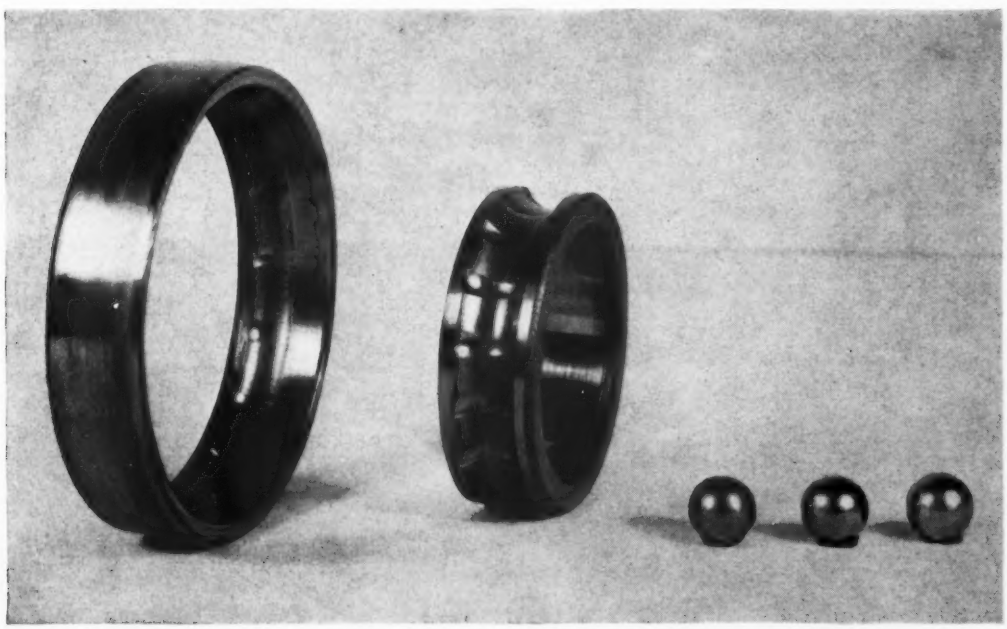

Figure 3—Failure of bearing as a result of vibration with bearing not rotating—a severe example of fretting corrosion.

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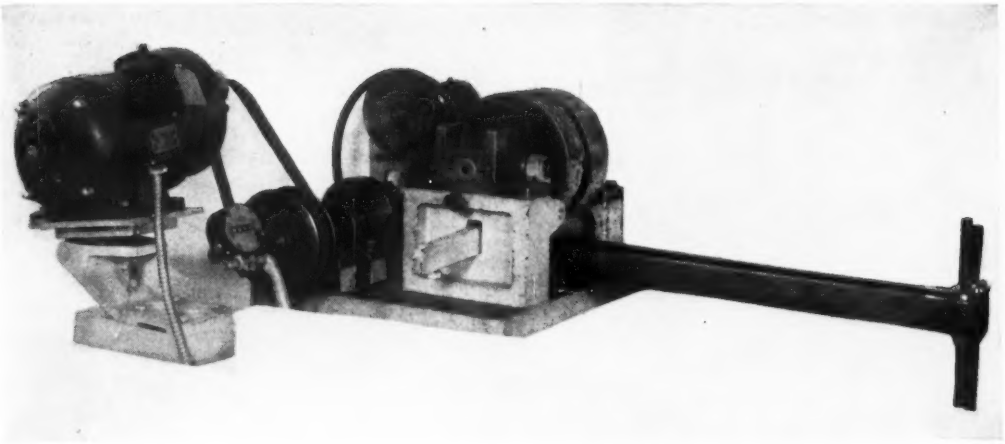

Courtesy of The Fafnir Bearing Company

Figure 4—Test machine used to evaluate friction oxidation (fretting corrosion) effects in anti-friction bearings. Bearing is oscillated through a total of 60°, performance is evaluated in terms of endurance life. Close-up view shows mechanism which produces oscillatory motion, with test bearing housing at extreme right.

Figure 5—Example of fretting corrosion on inner ring of ball bearing as a result of loose fit between ring and shaft.

reported, nearly all were conducted with test machines employing limited oscillating or reciprocating motion, either of selected anti-friction bearings or of special test samples in sliding or rolling contact. Provisions were made in many of the test programs for variations in loading, motion, surfaces, and lubricants over a wide range.

The test work and analytical studies that have been made have resulted in adequate differentiation of fretting corrosion from electrolytic or galvanic corrosion. In the latter, oxidation of metals is accomplished indirectly through the galvanic action of the metals with water. Metallic hydroxides (compounds of metal + oxygen + hydrogen) are usually formed, through the exchange of metallic ions with hydrogen from water. For such corrosion to take place, the setting up of an electrolytic circuit is necessary, and the presence of water or some other ionized solution containing oxygen and hydrogen is a must.

Although fretting corrosion also involves oxidation of the metal, the oxidation has been found to be more direct, and electrolytic conditions are not required. The necessary conditions for fretting corrosion to occur on ferrous metal surfaces have been found to be load, motion, and the presence of oxygen. The oxygen required for fretting corrosion is nearly always, if not always present, as it is very difficult to exclude entirely. In fact, the oxygen in the air dissolved in lubricants, or even that absorbed in the metal itself, can be sufficient to start fretting corrosion, which may then lead to surface failure through galling or fatigue.

Investigators agree that fretting corrosion is primarily of mechanical rather than chemical nature; however there is not complete agreement on the exact nature of the mechanism by which it occurs. Tomlinson, in England, has stated that molecular effects and forces were at the root of fretting corrosion, which is held to be direct oxidation of the surface as a result of high local heat from severance of cohesion bonds between the surface molecules.

Support is given to this theory by several of the pertinent findings listed by Tomlinson as a result of his studies. These are:

1. Corrosion appeared to occur with little regard to the magnitude of the normal pressure at surface interfaces.

2. The severity of corrosion was increased with more highly finished surfaces.

3. Corrosion occurred with very small relative motion, of the order of molecular dimensions.

Some investigators have preferred the explanation first published by Fink, who concluded that wear resulting from fretting corrosion was caused by successively producing and rubbing off oxide surface films. In both theories, however, slipping is the real cause of trouble. Whether the oxidation

Figure 6—Aircraft propeller hub cone, of aluminum bronze, showing effects of fretting.

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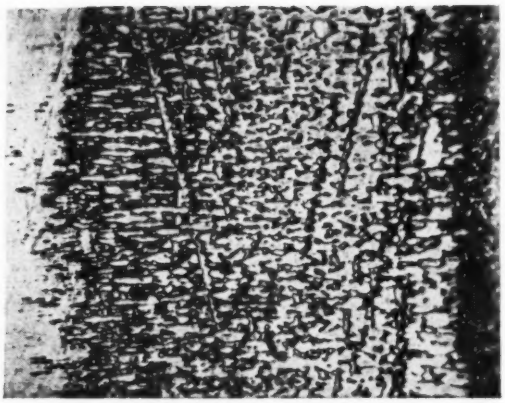


Figure 7—Photomicrograph of discoloration due to fretting corrosion on race of ball bearing at ball track. (500 X — Unetched).

is a secondary effect resulting from frictional heat from severed cohesion bonds due to slipping, or whether slipping rubs off protective oxide films, permitting corrosion to advance at a rapid rate, may not be critical in handling and solving problems of fretting corrosion. In fact, there is ample evidence that the mechanism may proceed either way in separate instances, dependent upon the loads, degree of motion, materials, and other factors involved.

This was recognized some time ago by Almen, who wrote that probably the conclusions reached by each of the several previous investigators whose results he had reviewed were justified within the limitations of their tests. In the same paper, the author also stated that Fink's theory of wear oxidation appears to meet most of the requirements in regard to false brinelling of ball and roller bearings in service. It was pointed out that this does not mean that wear of other machine parts in service can be explained by this theory. For instance, there are known conditions under which an oxide film on rubbing surfaces is beneficial.

Identification

An aid to identification of fretting corrosion and conclusions as to its nature as revealed by investigations at the Beacon Laboratories of The Texas Company have been summarized as follows:

"All cases of fretting corrosion received from the field to date have been accompanied by a reddish-brown deposit resembling mill scale. In one case concerning a deposit from specimens of machine parts, an analysis was performed using X-ray diffraction. This revealed that the deposit contained iron, copper and Fe_2O_3, being approximately 30 per cent Fe_2O_3. From this it may be concluded that, where steel or iron parts are involved, Fe_2O_3 is undoubtedly a product of fretting corrosion and hence X-ray diffraction offers a tool of fairly positive identification. In addition, in so far as the field is concerned, the usual occurrence of this deposit on iron or steel surfaces is of interest for identification purposes.

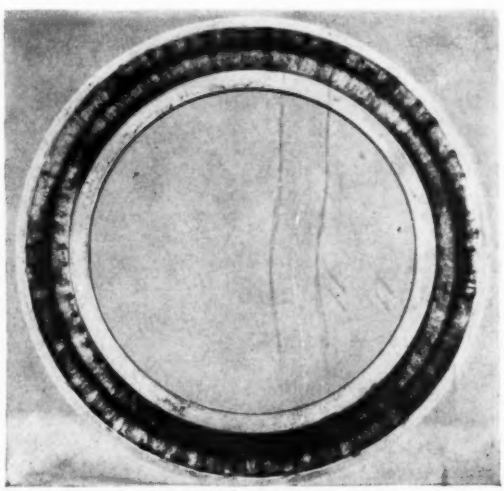
"Furthermore, it is evident that the Fe_2O_3 is not a product of a corrosion reaction, but may be considered to be the result of direct oxidation of iron as a consequence of some type of high load-high temperature operation. This would, of course, indicate that fretting corrosion is simply the raising of the temperature of a part to such a point through friction or reverse stressing of molecular proportions so that in the presence of oxygen, direct oxidation of the surface may occur."

Slipping

As mentioned above, slipping or the presence of sliding motion at the interface of loaded surfaces is a critical factor in establishing conditions for fretting corrosion. The limits of the required motion in any given case may vary from an almost infinitesimal quantity, of the order of molecular dimensions, up to the motion critical for oil film wedging, for lubricated surfaces.

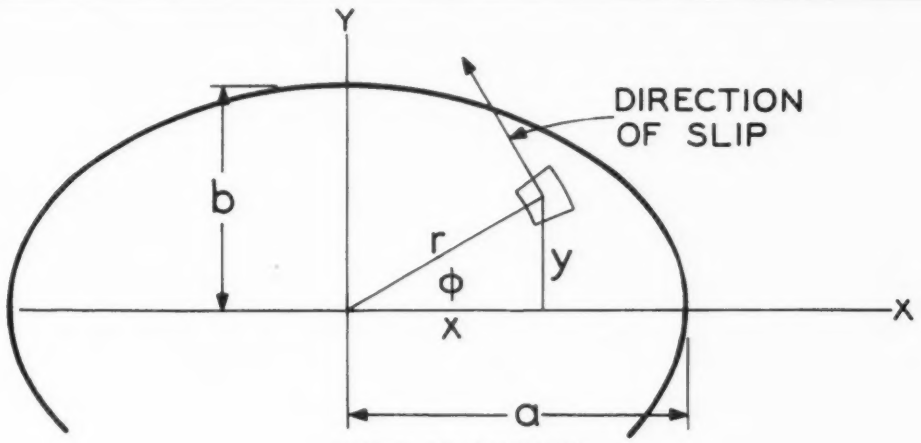
In ball bearings, slipping cannot be entirely eliminated, in spite of the predominant rolling motion, due to the peculiar conditions attending the motion of the flattened contact surfaces as a result of elasticity of the steel balls and races. The flattened contact surfaces assume an elliptical shape under load, as shown in Figure 9. As the ball rolls, slipping occurs on portions of the contact area although the center may still maintain true rolling motion.

In the case of a roller bearing, the contact area is rectangular instead of elliptical, and the center



Courtesy of The Fafnir Bearing Company

Figure 8—Fretting corrosion on variable-pitch propeller blade retention bearing.



ELLIPSE OF CONTACT*

Although in the ideal case, contact between the balls and races of a ball bearing occurs only at mathematical points, actually the elasticity of the materials results in a flattened contact area, of finite size and elliptical in shape.

In the ellipse of contact, as shown above, slipping motion involves rotation about the origin. Thus, at any point a distance, r, from the center of contact or origin, the direction of slip is normal to the radius vector from the origin to the point. This slipping is responsible for the friction torques of ball bearings. An analysis has been developed which, through integration of the slipping moment throughout the contact area, permits calculation of the friction torque for pivot type ball bearings. The presence of slipping as a characteristic of the motion of balls and races is of interest in studying the mechanism of fretting corrosion.

*Diagram and analysis from "Sliding Friction of Ball Bearings of the Pivot Type", by Poritsky, Hewlett and Coleman, Journal of Applied Mechanics, December, 1947, A.S.M.E.

Figure 9—Ellipse of contact of ball bearing.

of rotation a line, rather than a point. Sliding motion occurs on part of the contact area as the roller rotates, as a necessary result of the flattened contact area.

Under normal operation of a lubricated anti-friction bearing, an hydrodynamic oil film, or at least a thin film, is maintained between the sliding areas of the contact surfaces. If the load is increased sufficiently to cause metal contact, failure of the balls or rollers and races will occur, usually through welding and pitting. Under the relatively small oscillation or vibrating motion which is within the field of fretting corrosion, insufficient motion of the balls, combined with reversals in direction, prevents the establishment and maintenance of an oil wedge. Thus metal to metal contact occurs, with resultant heat. Oxidation of the metal surfaces results. Oxidation of the lubricant as a result of this heat, leading to the formation of acidic materials, serves to increase the severity of the corrosion.

Effect of Load

The foregoing may explain why increased load has been found by many investigators to increase the severity of fretting corrosion of anti-friction bearings. Higher normal pressures result in larger contact areas between the balls or rollers and races, as well as in greater frictional heat. Referring to the analysis of Fig. 9, greater contact area results in greater slippage or sliding motion, thus increasing the tendency toward fretting corrosion.

On the other hand, the effect of load upon fretting corrosion of mechanisms other than anti-friction bearings is not so consistent. Although with a given motion, the severity of corrosion usually has been found to increase with increased surface loading, in some machined parts, such as clamped or pressed joints, an increase in the surface loading is beneficial in reducing the severity of corrosion. This would appear to apply particularly to fretting corrosion cases which are due to induced or externally imposed vibrations, on which the motion may be reduced or eliminated by increasing the surface pressure.

Variations in clamping loads due to vibration have been found sufficient to produce fretting corrosion, with only very slight motion. Increasing the clamping load to prevent all motion, and at the same time minimize the effect of the variations in load due to vibration, is not always effective in such instances. An effective fix is sometimes provided by installing a relatively soft shear coating or plate between the clamped surfaces, which leads to a discussion of the effect of surfaces themselves.

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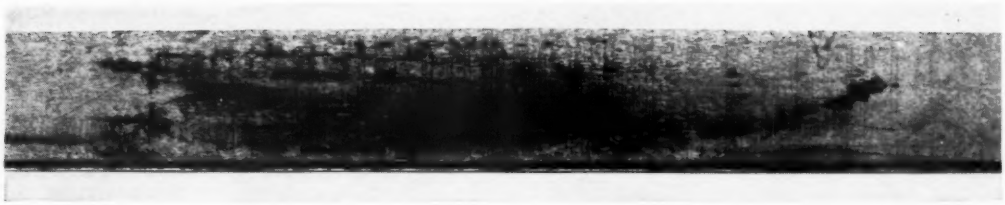


Figure 10—Rotated view of segment of outer surface of ball bearing outer ring, showing fretting corrosion as a result of slight relative motion between ring and housing during operation with steady static load.

Effect of Surface Finish and Materials

Tomlinson's conclusion, that the severity of fretting corrosion is increased with more highly finished surfaces, has been confirmed by other investigators. Another pertinent finding from the literature is that corrosion of steel surfaces of the same degree of surface finish is more severe than that of surfaces of different finish, under the same conditions.

Similarly, it has been reported that surfaces of like materials are more susceptible than those of unlike materials. Surprisingly enough, in view of its resistance to electrolytic corrosion, stainless steel has been found to be one of the materials most susceptible to fretting corrosion, although many other types of steel are affected to nearly the same degree. Combinations including nickel as one of the materials are among the least susceptible surfaces, and chromium plating of one of the surfaces has also been found effective in reducing the severity of fretting corrosion in some instances.

Two types of surface coatings have been proposed to aid in reducing or eliminating fretting corrosion under special circumstances:

1. A lubricant or shear coating to reduce friction, or

2. A plated or treated surface to increase friction and prevent slipping.

The choice between these in any given case would necessarily depend upon the type of motion and surfaces involved and the direction from which benefit might be expected to be obtained—whether from a reduction in friction or from an increase in friction to reduce or eliminate sliding motion. Often, trial and error methods must be applied in order to determine the direction of benefit.

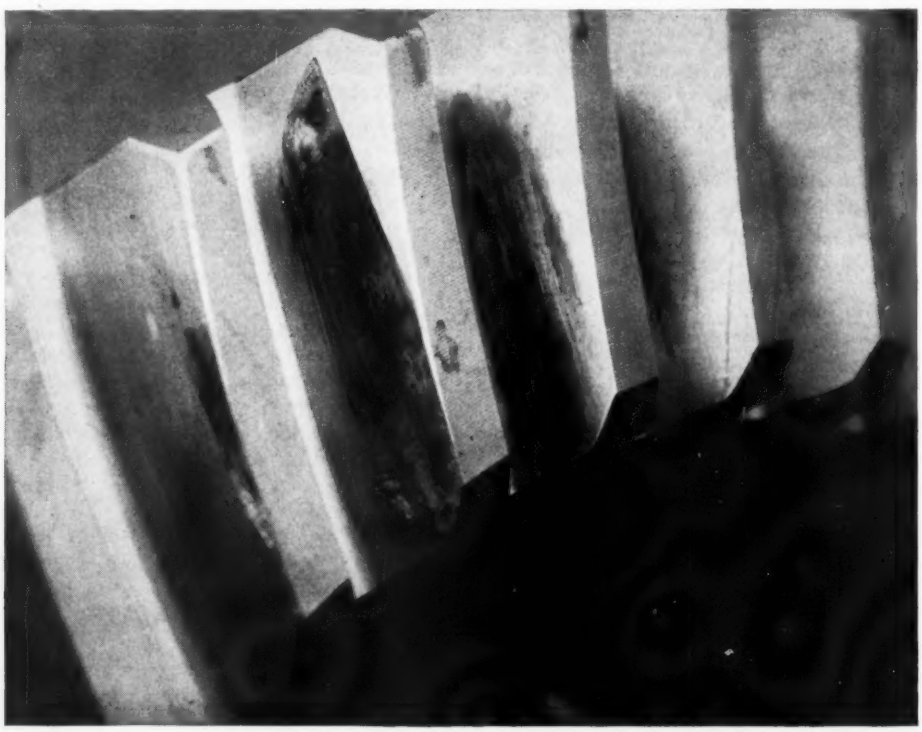
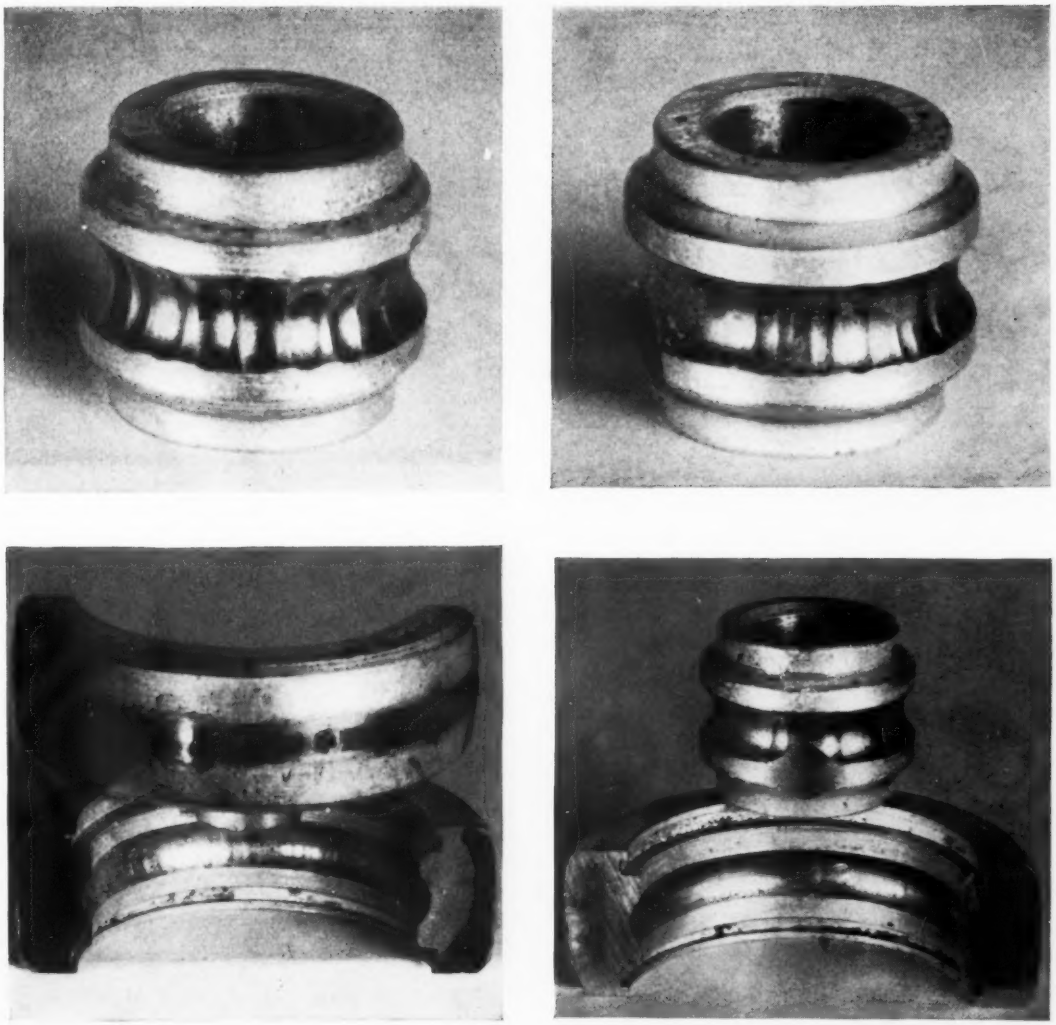


Figure 11—Severe fretting corrosion on aircraft gears as a result of high frequency vibration under high load.



Courtesy of The Fafnir Bearing Company

Figure 12—Effects of friction oxidation (fretting corrosion) on inner and outer rings of aircraft control bearings. Bearings are used in pulley controls which operate only with intermittent, oscillatory motion through a small amplitude.

GENERAL SOLUTIONS

Unfortunately, there is no single solution that may be generally applied to all problems of fretting corrosion. Since the factors of motion and load are most vital in promoting fretting corrosion, elimination or modification of one or both factors affords the best approach to a solution.

Other suggestions for solution, some of which have been touched on above, include:

1. Elimination or exclusion of oxygen at contact surfaces.

2. Provision of an adequate lubricant or surface coating to reduce friction.

3. Provision of a plated or treated surface to increase friction and prevent slipping. (This, obviously, is the converse of 2.)

4. Provision of a gasket to absorb motion without metal pick-up or welding.

5. Increasing the hardness of one or both surfaces.

6. Inducing residual compression stresses at the contact surfaces through shot peening, surface rolling, nitriding, or carburizing.

7. Increasing motion in the operating region to a degree sufficient to maintain a protective lubricant film.

In discussing these suggested solutions, it should first be noted that not all are applicable or can be considered for a given problem, nor is their effec-

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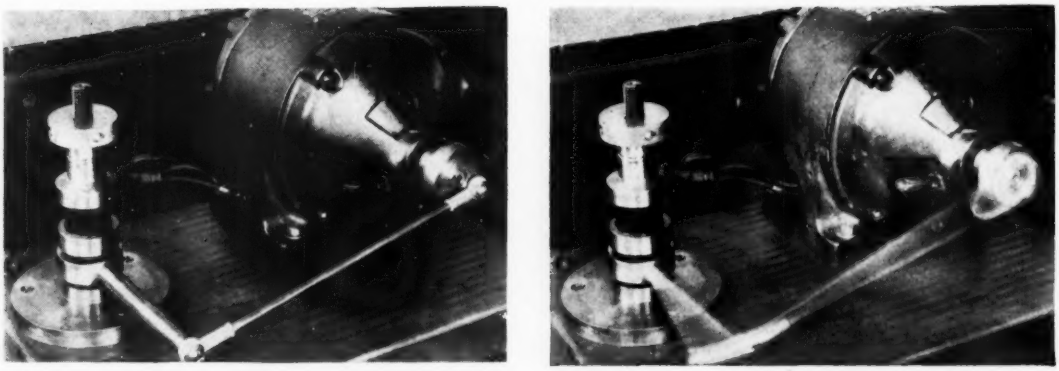


Courtesy of The Fafnir Bearing Company

Figure 13—Two views of oscillating test machine used for study of friction oxidation: Left view, machine at rest; Right view, machine in motion. Relative degree of friction oxidation is gaged by weight loss of thrust washers of test bearing, which is oscillated through a total of 12°.

tiveness uniform. For instance, in many machines, elimination of oxygen is impractical, if not impossible.

A shear coating, such as lead plate, has been found effective in some instances in reducing friction and alleviating the resultant fretting corrosion. Use of a lubricant incorporating graphite has also been beneficial in some instances, although ineffective in others. One such successful application involved the torsional vibration damper of a medium speed Diesel engine, wherein the use of a graphited oil was reported to be effective in reducing fretting corrosion.

With regard to residual stresses, Almen has pointed out that shot peening offers the double advantage of inducing stresses and of increasing friction, which helps prevent slipping.

Figure 14—Spalling on cup of roller bearing from bus wheel, showing fatigue failure apparently following fretting corrosion.

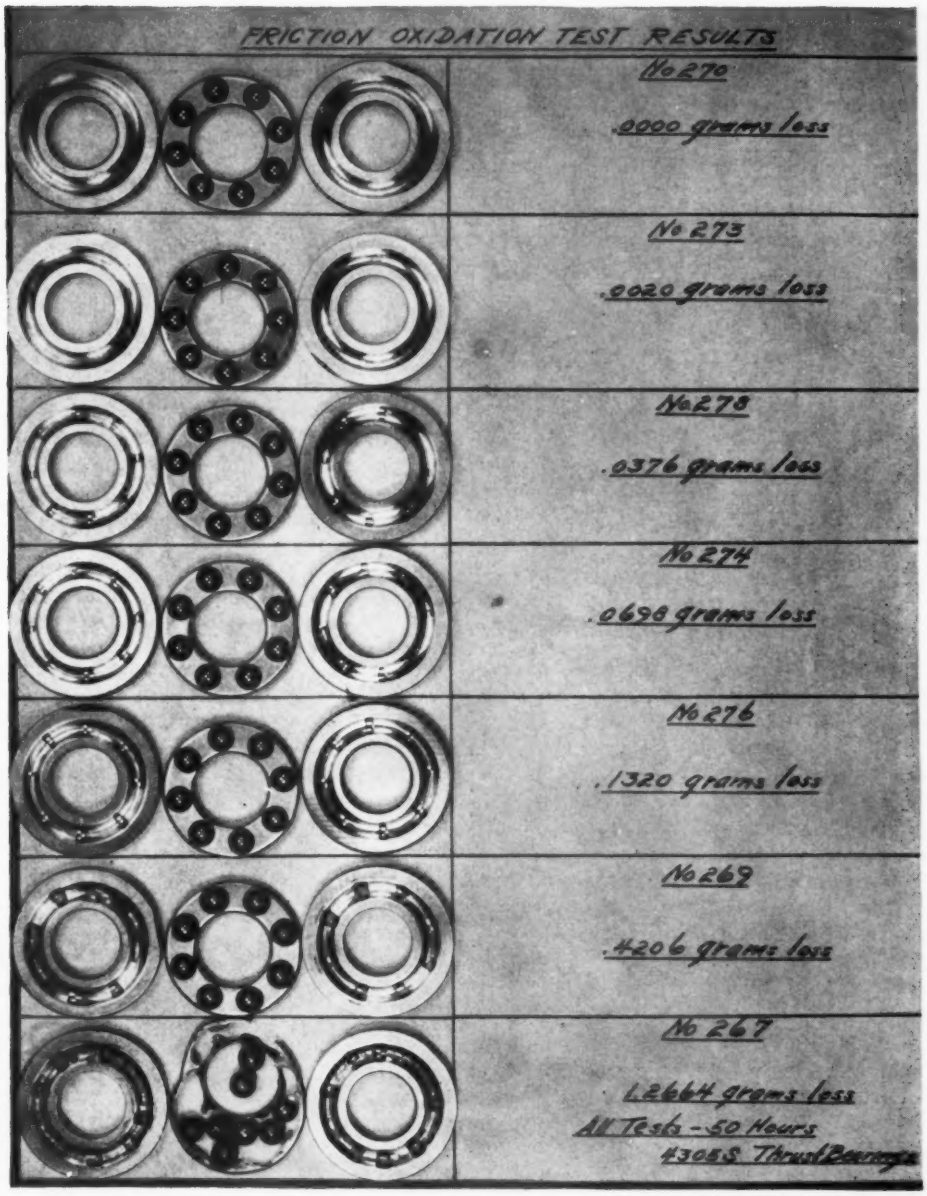
Lubrication and Lubricants

Solutions by means of lubricants have been investigated in sufficient detail to warrant special discussion. Such solutions are also of special interest to users and operators, as opposed to other remedies which can be applied only by machine designers or builders.

It has been found that severe fretting corrosion can be greatly reduced, although not entirely eliminated, by the use of low-viscosity, fluid lubricants. By excluding air, lubricants retard oxidation. Although high viscosity oils would appear preferable for this purpose, lubricants incorporating low viscosity and high tenacity have also been effective. Mobility of the lubricant, then, is important, as well as high film strength, in protecting the surfaces.

This has led to a recommendation of strong adhesive and extreme pressure (EP) properties for lubricants to be used in combating fretting corrosion.[1] Fluid rather than channeling lubricants are preferred by the same writer, who also lists high resistance to oxidation and deterioration as desirable properties of the lubricant. Submergence of contact areas with lubricant, where at all possible, has been recommended without exception by those investigators dealing with lubricants.

1 "Friction Oxidation," Hudson T. Morton, published by The Fafnir Bearing Company, 1946.



Courtesy of The Fafnir Bearing Company

Figure 15—Results from tests in machine shown in Figure 13, showing effect of lubricants under the accelerated conditions of the tests.

Submergence, coupled with the use of low viscosity, high-film strength lubricants appears to offer the most likely solution to fretting corrosion difficulties from the direction of lubrication. This direction (lubrication) is not always the most effective in a given problem and, besides, there are many problems to which the recommended practices can not be applied. It should be remembered, too, that lubrication has not been completely effective in eliminating oxidation, even under favorable conditions.

The development of "anti-fretting corrosion" lubricants does not appear too likely in view of the influences of load and motion upon the phenomenon.

Anti-friction Bearings

Since several investigations of fretting corrosion have dealt specifically with ball and roller bearings, the conclusions pertaining to these are of sufficient interest to list separately. Given below are the

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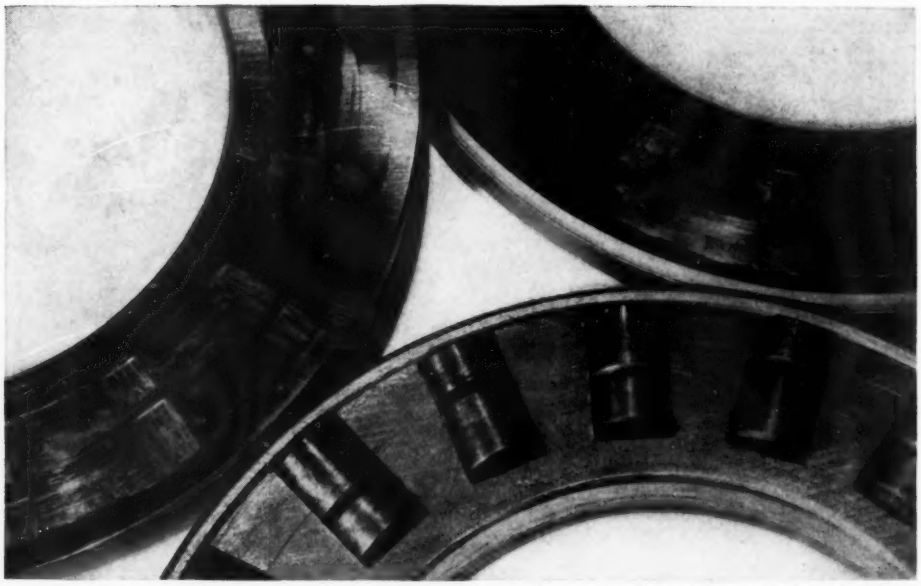

Courtesy Air Materiel Command U. S. Air Forces

Figure 16—False brinelling (fretting corrosion) of helicopter rotor blade thrust bearing.

recommendations of a large bearing manufacturer[1] for solution or alleviation of friction oxidation in oscillating bearing applications:

(1) Elimination of load and motion (vibration) factors affords the most desirable solution.

(2) Loads should be reduced at least to 50% and preferably below 35% of those given in bearing catalogs, using as the RPM one-half the number of reversals per minute.

(3) The total movement of the bearing should be sufficient to turn the balls or rollers at least 180°.

(4) Fluid lubricants with strong adhesive properties and high resistance to oxidation are preferred.

(5) Seals and enclosures should be provided to keep contact areas submerged in lubricant.

(6) Bearing looseness and machine vibrations should be kept to a minimum.

Investigations of fretting corrosion and allied effects in anti-friction bearings are continuing, although the problem is not critical with the industry in general, but rather with certain applications which by virtue of the operating characteristics are particularly susceptible.

Among these are grease lubricated, oscillating aircraft control bearings, as has been mentioned before. This application is under close observation by the military air services, bearing manufacturers, aircraft manufacturers and lubricant suppliers, all of whom are concerned.

CONCLUSION

Like many other technical problems, fretting corrosion has been one that has yielded to the impact of scientific investigation and study by industry and industrial laboratories. The problem is by no means solved, however, nor are all of the many questions involved adequately answered at this time. Complete solution or obtaining the answers to all of these questions will be achieved in more-or-less direct proportion to the efforts and pressure that are placed upon solving them by the many industries involved. The present article is in the nature of a progress report on investigations that have been reported up till now. It is not too optimistic to expect that future progress will result in a more complete understanding of the nature of the fretting corrosion problem and will eventually result in virtual elmination of the problem.

[1] Ibid.

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Additional references are included in those listed above.

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